PB-241 240

THERMAL ENVIRONMENTS AND PERFORMANCE

Andris Auliciems

Queensland University
Brisbane, Australia

January 1973

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

BIBLIOGRAPHIC DATA SHEET	1. Report No.	2.	PB 241 240

4. Title and Subtitle Thermal environments and performance	5. Report Date January 1973 6.
7. Author(s) Andris Auliciems.	8. Performing Organization Rept. No.
9. Performing Organization Name and Address University of Queensland, Department of Geography, Australia.	10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Organization Name and Address Department of Health, Education and Welfare, National Air Pollution Control Administration, Division of Health Effects Research, Research Triangle Park, North Carolina.	13. Type of Report & Period Covered 14.

15. Supplementary Notes
Now EPA ..

16. Abstracts

Although several reviews of thermal influences on performance have appeared during the past decade, none have succeeded in synthesizing the various experimental results. In the meantime, new evidence has been presented from several studies, particularly those in classroom situations. The present report takes a critical look at this recent work, and hypothesizing that to the human the degree of warmth is merely relative to its subjective perception, attempts to find common basis for comparison of levels of performance by different populations in greatly differing thermal environments. When viewed from the basis of levels of thermal comfort, the seemingly chactic information that is available can be drawn into some focus, and many of the apparent contradictions and erroneous interpretations tend to become considerabley diminshed.

17. Key Words and Document Analysis. 17a. Descriptors

thermal environments

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

Reproduced by
NATIONAL TECHNICAL INFORMATION SERVICE
US Department of Commerce
Springfield, VA. 22151

PRICES SUBJECT TO CHANGE

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Available from NTIS	UNCLASSIFIED	53
	20. Security Class (This Page) UNCLASSIFIED	22. Price 4.25-2.25

THIS FORM MAY BE REPRODUCED

PREFACE

Although several reviews of thermal influences on performance have appeared during the past decade, none have succeeded in synthesizing the various experimental results. In the meantime, new evidence has been presented from several studies, particularly those in classroom situations. The present report takes a critical look at this recent work, and hypothesizing that to the human the degree of warmth is merely relative to its subjective perception, attempts to find common basis for comparison of levels of performance by different populations in greatly differing thermal environments. When viewed from the basis of levels of thermal comfort, the seemingly chaotic information that is available can be drawn into some focus, and many of the apparent contradictions and erroneous interpretations tend to become considerably diminished.

RESEARCH ON THERMAL EFFECTS

Although certain experimental investigations have reported no loss of performance at very high temperatures (Pepler 1963), decreases have been observed in a number of others.

The earliest controlled laboratory experiments designed to compare performances under various thermal conditions, appear to be those conducted by the New York State Commission on Ventilation (1923). In a weight lifting experiment a number of different scores were obtained, one of which showed that 15% less work was done at 24°C (75°F) air temperature than at 20°C (68°F). In the inquiry into thermal conditions of schools by Vernon, Bedford and Warner (1930), a chain link assembly task took some 12% longer to complete by both men and boys at 10°C (50°F) than at 16.5°C (62°F) air temperature. An experiment on heat acclimatized men at a manipulative coordination task showed a 62% loss of accuracy and a 14% increase in performance time with 33°C (91°F) ET compared with 18.5-20.0°C (65-68°F) ET (Weiner and Hutchinson 1945). Vitoles and Smith (1946) used artificially acclimatized subjects, apparently fully clothed, and at three temperature levels found that on a long battery of tests of psychomotor and mental performance output at 30.5°C (87°F) ET was reduced when compared to that at 26.5 and 23°C (80 and 73°F) ET.

Mackworth (1946, 1950) applied various extended vigilance and physical effort tasks to artificially acclimatized servicemen and found that all performances

showed deterioration at 30°C (86°F) ET.[1] He concluded "There is a critical region on the atmospheric temperature scale above which most acclimatized men dressed in shorts will not work effectively indoors. This region lies between the effective temperature readings of 83°F and 87.5°F, i.e. between the dry bulb/wet bulb readings of 90/80°F and 95/85°F when the air movement is 100 feet per minute. This conclusion applies to all forms of intensive work, both physical and mental" (Mackworth 1950, p.151).

Confirmation of a critical temperature zone has also come from Carpenter (1950), Pepler (1956, 1958) and Watkins (1956). These three investigators conducted what may be considered a series of experiments comparable to those of Mackworth's, but Pepler employed naturally acclimatized British servicemen in Singapore and Watkins used indigenous West African soldiers. In both the latter experiments performance decrement was observed at 30°C (86°F) ET, but neither experiment could support Mackworth's earlier conclusions that performance decrement is a logarithmic function of thermal levels, nor could it be shown that performance was independent of incentives. Pepler (1958) found that the best performance with no incentives was worse than the worst performance with incentives. Of particular interest is Pepler's (1958) discovery of a statistically significant decrement ($P < 0.05$) at 24.5°C (76°F) ET in comparison to 81°F (27°C) ET at two tests ; one a well practised tracking task and the other a complex mental task.

---

[1] Mackworth actually reported 30.8°C (87.5°F) ET having erroneously used the normal scale of effective temperature, and not the appropriate basic scale, as his subjects were stripped to the waist (Pepler, 1958, Watkins, 1956).

While giving no information concerning the state of acclimatization of their subjects, Teichner and Wehrkamp (1954) found loss of performance at a sensory-motor coordination task 8.5°C (15°F) above and below air temperature of 21°C (70°F). The subjects in the experiment wore normal clothing and the results are of significance in view of the very short duration of exposure to four temperature levels at 13°C, 21°C, 29.5°C and 38°C (55°F, 70°F, 85°F and 100°F). The authors noted that performance decrement was greater at 13°C (55°F) than at 29.5°C (35°F) and concluded that man's sensitivity to cold was greater than to warmth.

Russell (1957) applied a battery of finger sensitivity, strength of hand grip and tracking tests to a large number of unacclimatized enlisted personnel in a very wide range of air temperatures, 10°C - 40°C (14°F - 104°F) varying in steps of 10°C (18°F). The results demonstrated a trend of increasing proficiency with increasing temperatures, becoming asymptotic above air temperature of 20°C (68°F) while in one task, performance deteriorated 10°C (18°F) above and below this temperature.

It is of interest to note that most of the early research on thermal effects was actually carried out under conditions more approximating real life situations, and evidence that the more extreme thermal environments may be detrimental to work was first presented by field studies in industry.

Accident rates in ammunition factories appeared to increase by some 30%

in temperatures above 24°C (75°C) and below 10°C (50°F) (Osborne et al 1922, Vernon 1918). In coal mines absences due to accidents showed a substantially higher incidence in hot seams (Vernon et al 1928, 1931) and at 27°C (81°F) ET less coal tubs were filled and more frequent rest pauses taken than at 19°C (66°F) ET, (Vernon et al 1927). Production in heavy glass and metalurgical industries (Vernon 1919, 1920; Farmer et al 1923) showed a marked decrease during the hottest months of the year, and in textile industries (Weston 1922, Wyatt et al 1926) linen and cotton weaving production decreased above wet bulb temperatures of 21-23°C (70-73°F). Recently Link and Pepler (1969) compared the earning of women sewing in a non-air conditioned apparel factory to the daily fluctuation of indoor temperature and found that production decreased significantly over the range 24 to 32°C (75 to 90°F).

Field studies of thermal influences on mental performance, however, are quite scarce, and all with one notable exception (Seymour, 1936), have been conducted only during the last decade. These studies have involved learning situation, undoubtedly due to the awakening interest of educators and school designers, but also because of the limited applicability of the type of evidence offered by laboratory experiments. It is appropriate that a critical review of the recent findings under relatively normal work conditions be attempted at the present time.

Research in learning situations

Seymour (1936) aimed to discover whether the mental work of children was affected by varying conditions of air temperature and ventilation within the range prescribed by Vernon et al (1930) 13 -15.5°C (55-60°F) with cooling power of 7.*

* related to air movement and temperature and measured by Kata thermometer

The experiment in a school in London, England, extended over 9 weeks (October - December) of which the first five were devoted to practice and the last four to test sessions during which thermal conditions were controlled as much as possible. Over 500 children, aged 9-13, participated, being divided into two groups "Extensive" and "Intensive" Sections. Performance was measured by Kraepelin sheets, a continuous single figure addition task with the numbers arranged in columns alongside which answers were written. The test was applied twice daily at 10 and 12 o'clock for 5 minutes to the Extensive Section and once for 20 minutes to the Intensive Section.

In the Extensive Section a time signal was given at the end of each minute at which a new column of additions was started, and the total number of additions for each minute recorded in exercise books by the children themselves. Average scores per minute per day per section were later calculated as was the average per minute per week and the differences between the 10 and 12 o'clock sessions determined.

The Intensive Section, composed of 30 girls, was given a signal every five seconds at which a line was placed after the last addition performed. The results of the 240 five second intervals were again recorded by the children, and averaged daily decreases in output for each week were calculated and taken as a measure of fatigue.

Desired thermal levels were partly achieved by regulating the hot water boiler supplying radiators and adjustment of windows. However, the temperatures could only be regulated to within - $2^{\circ}F$ ($1^{\circ}C$) and the cooling powers were also measured very approximately. Air temperature was measured by an ordinary dry bulb thermometer and the CP by a standard Kata thermometer with readings taken at

two points at a level of 3 feet (92 cm).

Complete results were obtained from 290 children in the Extensive Section and several different estimates of performance determined. In one, the score was taken as the average number of additions per minute per session per week for each child for both the 10 and 12 o'clock sessions. The percentages of children gaining or losing on this score at the 12 o'clock session were determined, and appear in the first two columns of Table 1. Average additions per minute per session per week were also calculated for the whole sample for each of the two sessions separately and the increase or decrease of the 12 o'clock session over the 10 o'clock session in each week were expressed as a percentage of the 10 o'clock output. This percentage increase or decrease appears in the third column of Table 1.

Table 1 Scores and Thermal Environments, Seymour (1936)

	% gaining	% losing	Average Score	Air temperature °F	Cooling Power
Week A	53	44	+0.9	60	6.0
Week B	63	35	+2.1	58	8.5
Week C	40	58	-1.3	54	8.5
Week D	51	48	+0.4	60	7.0

Increases from the first to the second session were apparently taken to equate with high working efficiency. The percentage increases in output for weeks A and B over week C were statistically significant but no statistically significant

differences were evident between weeks A, B and D. Neither were significant differences observed between the sexes nor age ability groups.

In the Intensive Section, the percentage average losses in production from the 1st to 20th minutes showed no statistically significant differences between the weeks, but it was found that the greatest reduction occurred in week C and the least in week B. Moreover, on comparison of the average production curves of the weeks, it was evident that output in week B began a consistant drop during the 13th-14th minute while in weeks A, C and D the drop began earlier during the 10th-11th minute. This, Seymour believed, indicated that the fatigue effect was delayed in week B in comparison to the other weeks.

Fifteen teachers at the school were asked to assess the four conditions, according to a thermal sensation scale, as to the suitability of each week for teaching purposes and not from any consideration of personal comfort. By average votes, week B was considered most suitable and D, C and A were ranked in that order..

Although the treatment of certain aspects of the problem is vague, Seymour's conclusions seem to be justified that the conditions of week B, 14.5°C (68°F) with CP of 8.5 (this gives approximately 22 cm/sec. air velocity) were most suitable for schools, while 12°C (54°F) with CP of 8.3 (approximately 15 cm/sec) being the least suitable. In terms of Teq, the optimum conditions would appear to have been at approximately 12-135°C (54 - 56°F) Teq (Seymour 1939).

Peccolo (1962) investigated the effects of thermal environments on "mental

efficiency and learning" in classroom situations, hypothesizing that there would be no differences given "recommended ideal" and regular thermal conditions.

The study was conducted in the Lennox Research School in Des Moines during March-May. The Research School consisted of two nearly identical specially constructed and adjoining classrooms in which temperatures, humidities and ventilation rates could be varied with considerable precision.

Two sets of pupils of both sexes, aged 10-11 years from two schools acted as subjects. The first set was drawn from the Canary Lake School where two classes were hetrogenously grouped so that both had covered the same amount of instructional material. Twenty-two pairs of matched students (one set of pairs acting as experimental and the other as control groups) were selected for comparison. Selection of pairs was made principally on the basis of achievement scores on the Iowa Test of Basic skills (I.T.B.S.), and it appears that only little rearranging of classes was necessary. These matched pairs were termed the "low" set since their mean I.T.B.S. scores were lower than that of a set of "high" pupils similarly chosen from two classes, at the Saylor Center School.

A full explanation of the investigation was given to the subjects verbally, and their parents in writing. The choice of the "experimental" groups, i.e. those occupying the "ideal" or "model" climates was made by headmasters, but the subjects were not informed of the selection. The "ideal" conditions had been selected on the basis of opinion expressed in a number of publications, and this was maintained at 22-23.5^{o}C (72-74^{o}F) air temperature, 40-60% relative humidity and ventilation rates of

10-20 cm/sec. The control room was kept at conditions typical of home schools at 22-27°C (72-81°F), 35-67% and 5 cm/sec. The average difference in air temperature appears to have been about 3°C (5°F).

Three types of paper and pencil tasks resembling ordinary classroom activities were chosen : Clerical and Routine Activities (varying in length between 30 seconds and 2 minutes, performed once a week), Reasoning Activities (2 to 20 minutes long, some once a week and others daily) and New Concepts (films 13 minutes long and subsequent tests 15 minutes, presented 4 times over 3 weeks).

There were 10 tasks altogether, administered by Peccolo himself to the children at both schools during the weeks before and after the actual experimentation at the Research School. During the experiment which lasted for three weeks, the tasks were performed at the same time of the day with the researcher alternating between the rooms with the regular teacher.

Performance data were quantified by the number of correct responses by each subject and the results of each test were treated separately. Analysis of variance procedures were emplyed to compare the gains in scores (a three-factor design) throughout the experimental trials and to establsih differences at the post-experimental test (a two-factor design) of each of the "high" and"low" groups (levels) of both the experimental and control groups. Statistical significance was accepted at $P < 0.05$.

The results are summarized in Table 2, where significant F-values are marked "s".

Apart from the observable differences between the "low" and "high" level groups, the differences between treatment groups were consistant in that the experimenta'

group in all cases performed better than the control group. The null hypothesis was rejected for Reasoning (mazes, problem solving), and Clerical (checking names, checking numbers). Moreover, when the post-experimental trial was used they hypothesis was also rejected for the other Reasoning tasks (design completion, analogies and addition).

Table 2 Significance of F-values, Peccolo (1962)

	All Experimental Trials					Post-Experimental Trials	
Tasks	Levels (low/ high)	Treatment (control/ experi- mental)	Interaction trials X trent- ment	trials X levels	trials X treatment X levels	Treatment (control/ experi- mental)	Interaction treatment X levels
Reasoning							
mazes	s	s	s	.	s	s	s
design completion	.	.	s	.	s	s	.
analogies	.	.	.	.	.	s	.
addition	.	.	s	.	s	s	.
solving problems	.	s	s	.	s	s	.
Clerical							
checking names	s	s	.	.	s	s	.
cancelling letters	.	.	s	.	.	.	.
cancelling numbers	.	.	.	.	.	.	s
New Concepts							
films						.	s

Peccolo concluded that although the effects varied from task to task, the null hypothesis had to be rejected, and that the "ideal" environment was superior for

learning situations.

While in the choice of tasks, equating of groups, general administration and statistical treatment of data, little criticism can be offered, the validity of the results and conclusions may be questioned on several points. The most serious concerns the motivational aspects of the subjects. It is important to note that clear indication was given in two letters to the parents that the environments of the home schools were not "ideal". It also appears that implicit reference to this situation was also made to the subjects, although they were not informed which room they would occupy during the experimental sessions. This simple concealment was believed to be effective on the basis that children of this age would be too young to be concerned with thermal conditions. There is, however, no basis for this assumption, and quite to the contrary, comfort studies with children have shown them to be as sensitive to thermal levels as adults (Auliciems 1969a, Partridge and Maclean 1935). In view of the considerably cooler temperatures and the unaccustomed ventilation rates of the experimental group, it seems unrealistic to assume that this group would have failed to perceive their favoured conditions. As children were in no way segregated outside the classrooms, and since "enthusiasm" for the experiment had been clearly manifested, it is highly likely that information relating to thermal environments was exchanged and the location of the "ideal" room quickly identified. The use of the word "ideal" would have certainly indicated to the subjects the expectations of the investigation, and the increased response to such expectation is of course a well known contaminant.

Although the rate of air motion and degree of humidity are related to thermal exchanges from the body to the environment, these factors also independently determine other more qualitative aspects of the atmosphere. The physiologically imperceptible air motion of 5 cm/sec. as maintained in the control room, when compared to the appreciable 12-20 cm/sec in the "ideal" room would indicate "stuffy" against "fresh" environments (Bedford and Warner, 1939 , the two being not necessarily related to thermal effects. Moreover, there may have been other qualitative differences between the outdoor air supplied to the "ideal" room and the recirculated air in the control room. Thus due to the combination of generally lowered air temperatures, lower humidities and particularly the considerably higher ventilation rates in the "ideal" room, the environments in the study varied not only in the thermal properties as claimed by Peccolo, but also in a degree of "freshness". There has been some recent evidence showing statistical improvement of performance under conditions of decreased humidity and increased air motion independent from thermal properties (Auliciems 1972a), suggesting that it is impossible to determine whether the raised performance levels in the "ideal" room strictly refer to thermal parameters, a factor of "freshness", or a combination of both.

Finally, the level of achievement at any particular session would depend not only on the preceding temperature (ie. the accumulative effects on "learning"), but also those at the time of the experiment (ie. the immediate effects on "performance"). While at the laboratory these levels were controlled, no data are given on the thermal conditions at the last trials on return to the home schools, which presumably were non-air

conditioned. As the post-experimental trials were held during relatively warmer May, little importance can be attached to these results.

In conclusion, it must be stated that although several aspects of Peccolo's study raise serious reservations as to the validity of the observed associations, seen in retrospect the results are of considerable interest by virtue of internal consistency and frequency of statistical associations.

McCardle (1966) aimed to determine the effects on learning by two different thermal conditions as found in classrooms. As in the investigation by Peccolo (1962), the Lennox Research School was employed, with matched pairs of students being located in two thermally different environments. Although similar in basic concept, several differences are evident. Sets of 40 pairs of matched sixth grade students (on the basis of the ITBS and IQ scores) from two schools were divided into the two thermal groups. These were further classed into high and low ability groups according to their IQ, with further halving in each ability level and alternating between morning and afternoon sessions.

The experiment was run for approximately 7 weeks during October-December, the average thermal levels differing between the two classrooms by some $3^{\circ}C$ ($5^{\circ}F$) and the lower being at $21-23^{\circ}C$ ($70-74^{\circ}F$).

Tests included Routine Tasks (simple division, twice daily for 10 minutes), Rote Learning (French vocabulary, studied on 25 occasions for 5 minutes) and Conceptual Tasks (programmed science material on 19 trials without time limit). Scoring in all tests was for errors, and the time required for completion in the latter.

Comparison was made between overall mean achievement scores of the two thermal groups, ability levels, different times of day and the various interactions. Apart from significant differences between ability groups, analysis of variance showed significant associations ($P < 0.05$) in the programmed material in which fewer errors were made and less completion time was required in the "ideal" thermal environment. McCardle concluded that there was evidence of significant thermal effects on conceptual tasks but not on rote learning or routine tasks, although scores at these had also been higher.

Regretably this report is difficult to evaluate due to absence of information, particularly relating to methodology and problems of test administration. As in the previous study by Peccolo (1962) no distinction was made between thermal and ventilation parameters, and the suggested causality must be questioned. With the type of analysis of results as used by McCardle, it is impossible also to determine whether the overall mean test scores reflect only immediate performance decrements or elements of accumulated learning over the whole period of the experiment. The author makes no reference to motivational aspects, nor to the introduction of the subjects to the experiment (a letter similar in content to that of Peccolo (1962) had been sent to parents) McCardle stresses, but does not elucidate, that every effort was made to conceal the location of the "ideal" room. As in the case of the previous study at the same location, the success of this must be doubted. In a third study by Hansen (1966), it was found that a sample very similar to McCardle's forced a change in administration of the programmed material by looking ahead in the books for the answers. No

reference to such a problem is made by McCardle, and it must be noted that all of his observations of statistical associations with atmospheric parameters occurred with this test material. In view of all these shortcomings, the interpretation by McCardle in particular is quite suspect.

A second experiment comparative to that of Peccolo's was conducted at the Lennox Research School by Hansen(1966). In contrast to the previous studies only one set of 22 matched pairs of fifth grade pupils was used. Wtihin this set 11 pairs were graded as "high" and the others as "low" ability groups. The experiment lasted for 9 weeks with all subjects, during which the "model" environment varied between 21 and 23°C(70 and 74°F) air temperature and the "control deviate" conditions were on the average some 4°C (7°F) higher.

The tasks consisted of Spelling (20 words administered by tape recorder on one day, revised on the second and tested on a third), Handwriting (taught 20 minutes daily for 4 weeks by specialist with evaluations once every week), Accuracy (hand operated machines used twice per week in duplication and simple arithmetical tasks, with scoring twice per week), Mathematics (arithmetic problems three times per week for 15 minutes, scored once per week) and Science (programmed material presented for 25 minutes three times per week and scored once).

Treatment of data closely followed the analysis of variance procedures as employed by Peccolo. Differences in final mean achievement scores of the last week were analysed in respect to ability groups and treatment (thermal) groups, and learning curves compared. While certain significant differences were observed between ability levels,

only one statistically significant relationship between performance and thermal conditions was evident. This occurred in the interaction between trial X treatment in the Accuracy test scores, but it appears that the rate of learning of the group in the "ideal" environment was slower than that of the control group. Hansen concluded that learning was not affected by the differences in thermal environments as employed in the study.

As in the case of Peccolo (1962) it is impossible to determine ventilation rates during the experiment. Nor is there sufficient information given to enable an assessment of the motivational levels of the subjects. The use of the term "learning" is inappropriate when the mean scores of the two thermal groups compared during the last week. As in Peccolo's (1962) study, a two-fold thermal effect could be expected in any session, and since the environments differed considerably during this final week, it is impossible to differentiate aspects of accumulated learning during the preceding weeks from test performance at the time of the first test.

A significant difference between this study and that of Peccolo (1962) is the seasonal factor. It is possible that due to heat acclimatization Hansen's control sample had been less affected by warmth during autumn, than Peccolo's non-acclimatized spring sample, and if so the identification of a common "ideal" thermal environment must be debated. There was, however, no attempt made by either study to identify relative positions of thermal neutrality, and direct comparison between the results is not possible.

McNall and Nevins (1967) hypothesized that academic achievement is facilitated

by thermal conditions in or near the comfort zone. Subjects were selected from four junior high schools in Florida, one of which (Oak Grove) was climate controlled. The daily mean range of air temperatures encountered and the percentage of days considered comfortable during the test periods appear in Table 3 together with the number of subjects in each sample. Committees of teachers prepared standard study guides for the subject areas : English, Social Studies, Mathematics and Science. During the year teachers were permitted to employ their own general teaching methods, but were requested to follow the guides. Pre-tests were conducted at the beginning (during the third week and in the first week of the summer term), and post-tested at the end (during the third week preceding the end of the academic year and the last week of the summer term). The tests employed were 14 in number covering the subject areas, plus standardized achievement tests and specially constructed ones.

The pupils were not informed of the special study and normal school routine was maintained. Achievement was defined as the difference between the mean scores of the pre-tests and the post-tests. Differences between group means were established by the t-test and significance accepted at the 1% level of probability.

Statistical analysis of the summer periods could not be carried out due to the insufficiency of subjects, while other comparisons between schools could not be made due to a marked superiority in student abilities. The most meaningful results concerned a comparison between the climate controlled Oak Grove and the non-climate controlled Tyrone School (see Table 3) in which near parity was evident in pre-test scores and teacher qualifications. Of the 28 possible comparisons over the two year

TABLE 3. TEMPERATURE (^{o}F BANDS) AND SUBJECT DISTRIBUTION IN THREE SCHOOLS DURING ACADEMIC YEARS 1961-63 (McNALL AND NEVINS 1967)

School	^{o}F												no. of days considered comfortable	percentage comfortable days	no. of subjects
	68	70	72	74	76	78	80	82	84	86	88	90			
Oak Grove		7	108	178	42	5	1						226	66.3	1188
Tyrone	1	9	34	66	64	60	38	31	33	5			184	52.4	2366
Pinellas Park		1	1	3	57	111	47	34	30	42	14	1	204	59.8	1625

period, 23 pre-test results showed no significant differences. Of these in the post-tests, Oak Grove gained significantly higher increases in 4 and Tyrone in 3 tests. In the remaining 5 tests, however, in which Tyrone had been signficantly superior in the pre-tests, the differences lost significance in 4 cases. Altogether out of the 28 comparisons, 8 changed in favour of Oak Grove and 3 in favour of Tyrone, with 17 mean scores unchanged. It appeared that in the climate controlled school English and Spelling tests consistantly showed higher improvement.

The authors concluded that there were strong trends favouring academic achievement in the climate controlled school Oak Grove. However, as noted previously by Pepler and Warner (1968) Oak Grove appears to have been superior in pupils, teachers and supervision, as well as other intervening variables relating to socio-economic backgrounds and climatic conditions during the periods of examination.

The experiment of Pepler and Warner (1968) is in contrast to the serious failures of the earlier studies in controlling the various intervening variables. Their design was based on the underlying idea that thermal effects should be evident from the way students study as well as how they perform. The experiment was conducted at Kansas State University's ASHRAE Environmental Laboratory which permitted a precise thermal and other physical factor control. Six different air temperatures were employed in conjunction with constant rates of humidity and air movement. A set of procedures was used which standardized variables such as clothing and pre-test behaviour.

A sample of 36 men and an equal number of women was drawn from the first year psychology class, eligibility being determined by states of health and attendance at each session. The sample was divided into six groups who studied a programmed

text (Holland and Skinner "Analysis of Behaviour")one day per week at a set hour. Each group was exposed to all temperatures which were arranged in a different order for each set of students. Performance was measured by the error rate at answering the questions in the text as well as the amount of time required to complete each assignment. The students were also required to record their subjective assessment of the effort needed to complete each assignment, and their thermal sensations.

The data were computer analysed for variance according to sex, level of academic ability and the session factors of temperatures and weeks. Measures of learning consisted of error rates (errors/time), working rates (work/time), percentage errors (errors/rate of work) and time required for completion of tasks.

The differences in percent error score and working rate were not statistically related to thermal environments, but associations were found with error rates ($P < 0.05$) and the time required to complete assignments. The reported effort was associated with temperature ($P < 0.01$), with least effort required at 27°C (80°F), which also appeared to be the thermal level for least error rate,but most time required. The data plots all reflected a "U" shape relationship between learning and temperature, with effort ratings significantly greater at 17°C (62°F) and 30°C (86°F), error rates at 17°C (62°F) and time to complete assignments at 20°C (68°F). No associations were found between temperature and performance by sex or learning ability.

In view of the unusually thorough control of variables and the somewhat unrealistic temperatures employed, this study should be classed as a laboratory experiment, but its simple replication of the private learning situation appears to enable

direct applicability to real life situations. It is a pity that quite arbitrary temperature steps had been chosen, and performance levels at neutrality were not gained. From the reported thermal comfort assessments it appears that mean maximum comfort occurred at approximately 25°C (77°F) - half way between two temperature steps. Thus the conclusion "students experienced increased effort, worked more rapidly and made more frequent errors at temperatures above and below a condition of 80°F" may be misleading as to the optimum thermal environment. Given also no statistical differences between any of the performance criteria seemingly between 22° and 29°C (72 and 84°F), little can be claimed except that the learning optimum was found to lie within this range. It is of interest to note however that the mid-point of the range nearly corresponds to reported thermal neutrality for the sample. Finally it may be debated whether the measure, time required for completion of the tasks, indicates more rapid work or a lack of willingness to prolong the effort. Given the latter interpretation, it appears that for this score a cool 20°C (68°F) may have been optimum.

In a very recent study, Pepler (1971) has attempted to gain data truly representative of actual classroom situations in a comparison of performance between climate controlled and non-climate controlled schools. Data were collected by teachers in three classrooms in each of six schools in the Portland (Ore) area - two grade (Spelling), two junior high (Social Studies, Spanish) and two high schools (Latin, Geometry, General Maths). In each set only one school was air conditioned. Scores in the subjects were collected twice every week by the regular teachers, who applied written tests designed by themselves a

at the same time of the day during two phases, one in spring (5 weeks in April-May) and the other in the fall (4 weeks in September-October). All except Spanish was taught by different teachers at the different schools, but apparently some coordination between courses was carried out by the investigator. Methods of marking tests, eligibility of individuals in samples, the comparative quality of teachers or pupils, and other socio-economical, educational or physical variables are not reported, but it appears that such variables were regarded as irrelevant with the "within" design of quantitative analysis. Scores were calculated as deviations from a "one month" average of each individual. It is not clear whether the students were informed of the investigation or whether standardized testing procedures were employed. No information is given as to the procedures employed by the different teachers in the non-climate controlled schools as regards opening of windows, but some of the high and low levels of warmth reached suggest the possibility of deliberately induced thermal stress. Indications of this is given by the author "....temperatures in Gresham Grade School were allowed to fall over the period more than in the other schools".

Dry-bulb temperatures and relative humidity were measured in each classroom at the end of the lessons, apparently in only one location. Air movement does not appear to have been more than approximated to a seemingly very high average of 50 cm per second (100 feet per minute) in the non-climate controlled schools. No indication is given of the dates of the tests to enable comparison with the actual temperatures, which are reported graphically showing fluctuations for all days.

In general the thermal environments in the non-climate controlled schools

show considerable fluctuations with initially moderate air temperatures around 24°C (75°F) but significant increases (up to 5°C) in later weeks (see Figs. 1 and 2). During Phase II, two of these schools show average temperatures of approximately 25°C (77°F) with perceptible warming trends in the final week. Temperature in the third school (East Gresham Grade) progressively decreases from 24°C (75°F) by about 3°C (5°F). Very little variation occurs in the air-conditioned schools, with air temperatures deviating by more than one degree Fahrenheit from 24°C (75°F) on only 7 days altogether in all schools in Phase I. During Phase II one school shows deviation of 2°F from 23°C (74°F) only once, and others altogether only twice from 24°C (75°F).

The correlation coefficients, calculated from each individual's scores and the temperature common to all subjects as one pair of variables, show a host of significant associations (See Table 4).

The author himself expresses surprise at finding significant correlations in the climate controlled schools. He explains this, however, as increased sensitivity due to the habitual exposure to equable warmth. If valid, these correlations are of great importance, since quite incredibly they show that temperatures deviating by only a degree or so, exert perceivable influences on performance levels, in real life situations! A closer look at the limited information presented, however suggests that

---

* There appears to be some discrepancy between reported degrees of freedom and the effective temperature table only is chosen. Obviously missing negative signs have been inserted from the dry-bulb temperature correlation table given in the report.

TABLE 4. ASSOCIATIONS BETWEEN PERFORMANCE AND EFFECTIVE TEMPERATURE (PEPLER 1971)

School / Class	Phase I			Phase II		
	r	df	P	r	df	P
Non-climate controlled						
East Gresham G.S.						
Spelling	- .195	649	.01	.066	448	N.S
Gardiner J.H.S.						
Spanish	- .109	497	.05	- .200	210	.01
Social Studies	- .154	498	.01	- .033	595	NS
Milwaukie H.S.						
Latin	- .145	399	.01	- .065	224	NS
Geometry	- .195	457	.01	.033	739	NS
General Math	- .055	428	NS	.034	412	NS
Climate controlled						
Powell Valley G.S.						
Spelling	.126	546	.01	.031	559	NS
Ogden J.H.S.						
Spanish	.141	435	.01	.015	304	NS
Social Studies	.313	449	.01	.024	513	NS
Rex Putnam H.S.				(?)		
Latin	.009	274	NS	- .215	373	.01
Geometry	.104	419	.05	.448	412	.01
General Math	.088	619	.05	.009	328	NS

these apparent associations may be spurious. For example, in Powell Valley Grade School (Spelling) in Phase I, the coefficient is positive and significant ($P < 0.05$), although during that time air temperatures departed from 24°C (75°F) on only a total of 4 days by only one degree upwards. How real these thermal differences are, is questionable, particularly given only one measurement at the end of the test, in only one location in the room, and with very approximate wind velocities deduced from design values. Moreover, if in some way the pupils were aware of the experiment in progress, the observed relationship is more likely to be the result of beginning and end spurts in performance, merely coinciding with the observed temporal locations of temperature increases (see Fig. 1).

Similarly also at Rex Putnam High School Latin and Geometry show positive correlation ($P < 0.01$) in Phase II, but again the increased temperatures occur at the end and the beginning. No other consistant correlations occur in Phase II, although the fluctuations are more frequent and seemingly greater at the other two schools.

It must be remarked that using dry-bulb temperatures instead of effective temperatures, did produce significant correlations in all the air-conditioned schools in Phase II. Quite amazing, however, is the appearance of opposite signs in the associations for Spanish and Latin, quite inconsistantly with non-air conditioned schools at these subjects, with other subjects in the same schools, with the same subjects in the same schools in Phase I and with the temperature distribution differences between Ogden J.H.S. and Rex Putnam H.S. The author attempts to explain these contradictory associations in terms of outdoor - indoor temperature contrasts, but is forced to admit

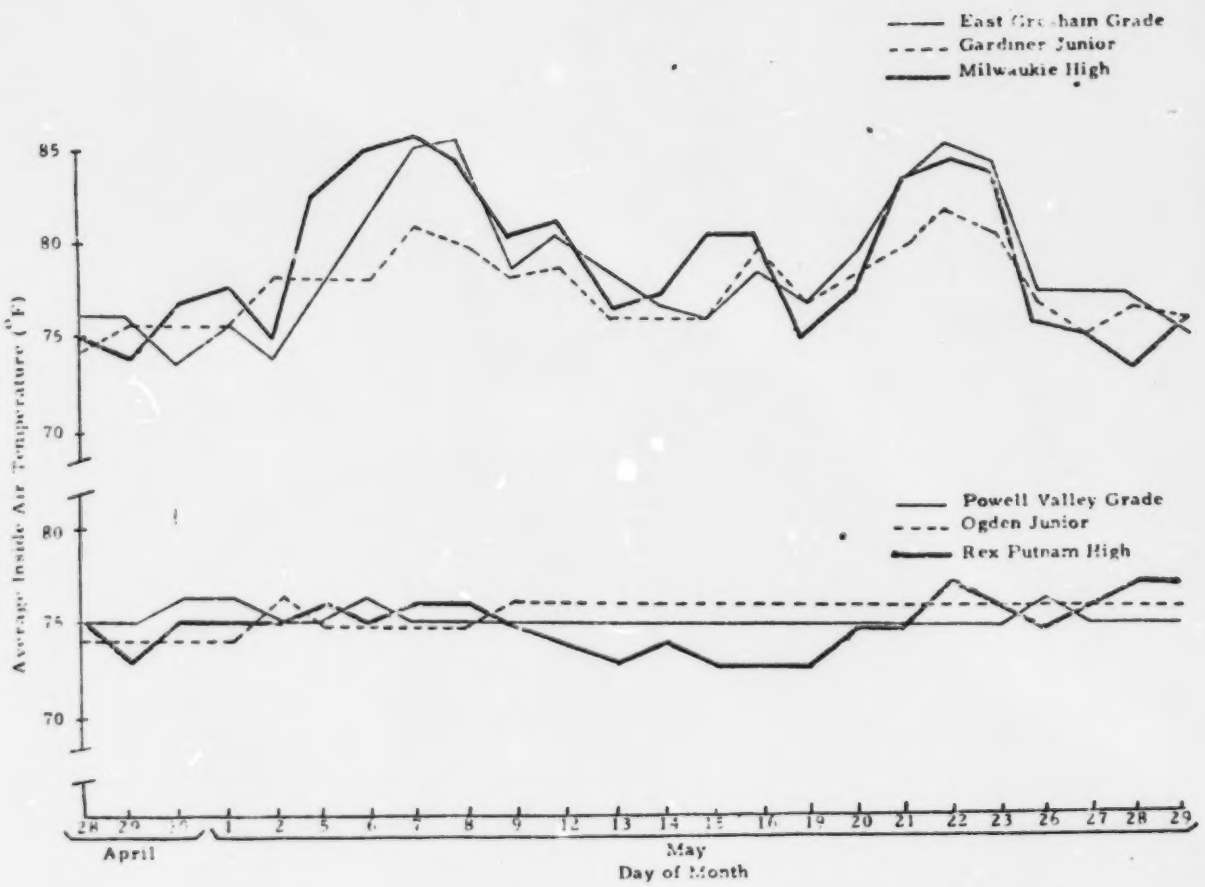


Fig 1. Daily average inside dbt — non-climate controlled schools, climate controlled schools, April 28-May 29, Phase I

that other variables apart from thermal ones may be held to account.

It must be concluded that in the current situation serious doubts must be raised as to the validity of all the observed associations in the climate controlled schools, particularly since the reported results show combinations of classes without accounting for between-group differences. Given the apparent lack of standardization of procedures and the doubtful reliability of the testing, little significance should be attached to the correlations.

While more credible, the associations in the non-climate controlled schools are similarly overshadowed by such possible intervening variables. In all these schools in Phase I, optimum performance temperatures (i.e. the lowest) occur at the beginning and the end of the period (see Fig. 2), again intimating possible spurts in performance. This suspicion is reinforced by the fact that in Phase II when temperatures do deviate in a more random fashion, showing the more unfavourable temperatures in the final week, no consistantly significant correlations are observable. Particularly interesting is the lack of associations in East Gresham G.S. with its steady and considerable decreases from the previously found optimum of 24°C (75°F) in Phase I. Pepler's suggestion that the lack of associations in Phase II may be explicable by seasonal temperature changes may be valid, but unless the control of other and apparently neglected variables is demonstrated, the climatic hypothesis must be rejected.

Given the well known phenomena of initial and end spurts in performance, which may have been a spurious co-variant to the distribution of temperatures, the internal inconsistencies of results and the lack of standardization of procedures, these

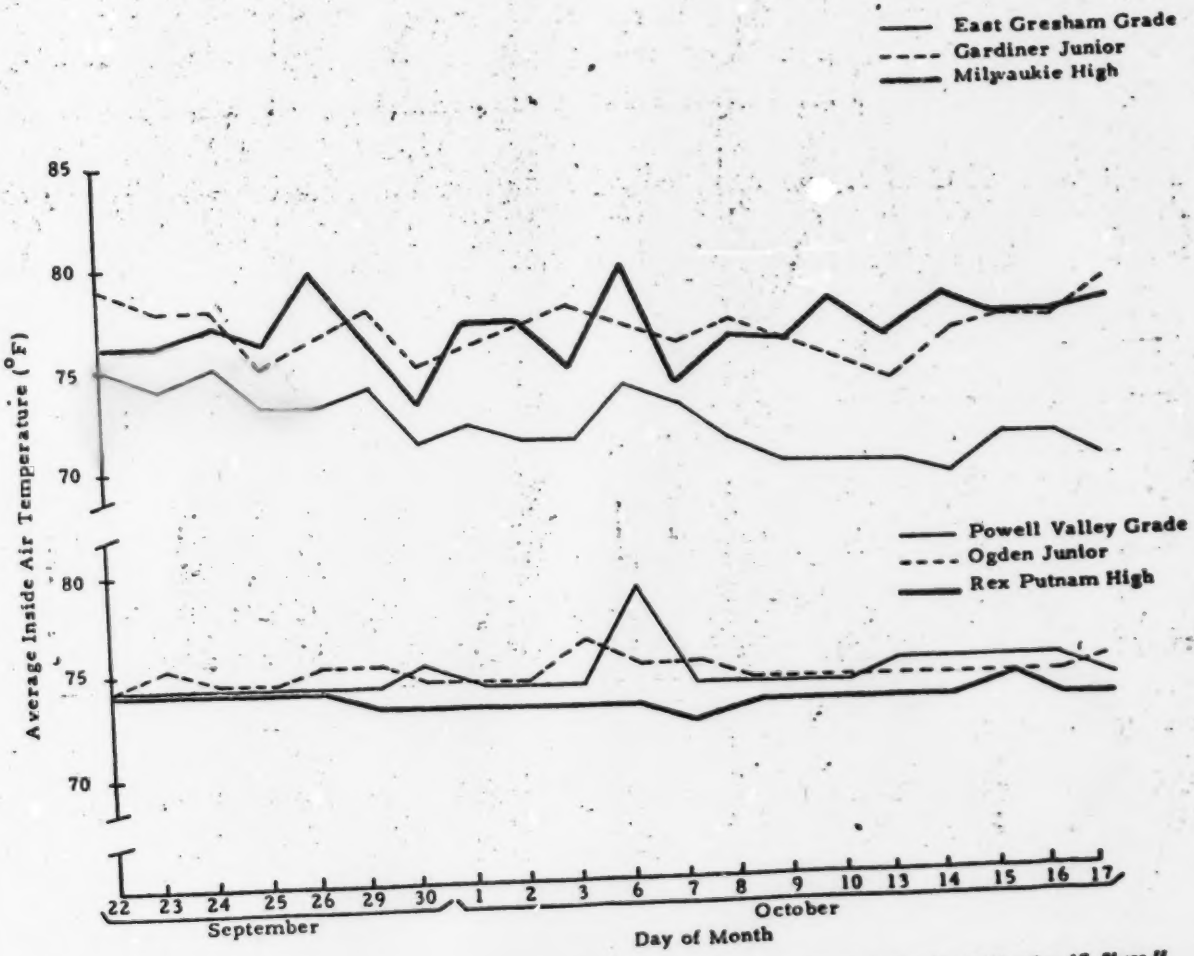


Fig. 2 Daily average inside dbt – non-climate controlled schools, climate controlled schools, September 22-October 17, Phase II

26a

results must be viewed with considerable caution, particularly the multitude of significant associations observed in the equable thermal environments of the air-conditioned schools.

Auliciems (1972b) tested several hypotheses concerned with weather conditions as well as indoor environments. As regards thermal levels, the main hypotheses related to the location of an optimum performance level within the subjective comfort zone.

As in Pepler's (1971) study, the basic idea underlying the investigation was to compare performance under customary conditions with naturally occurring temperatures. The study was conducted during winter months (1964-65) in Reading, England, where performance and thermal data were gained from 23 classes in 19 schools, including Secondary Modern, Grammar and Public Schools, none of which were climate controlled. Over 600 pupils aged 11-16 participated under normal school conditions.

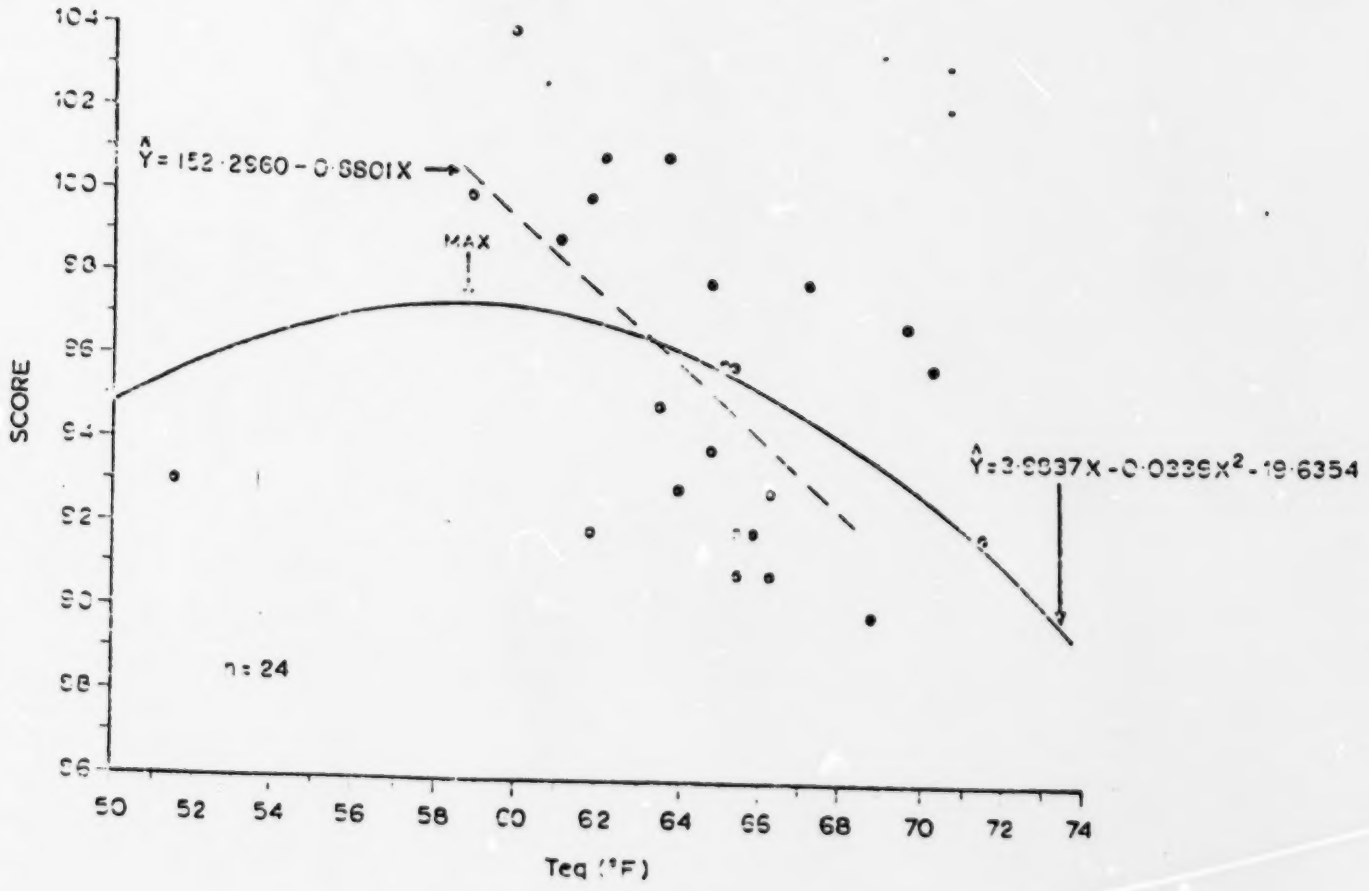
The tasks were paper and pencil types, chosen to represent typical daily "mental work" requiring a continuous response, or a high degree of "concentration". In order of decreasing intensity of response these were : Continuous Addition (one-hour) scores being the percentage ratio of additions performed in second half of test to those in first half, and the total number of additions expressed as deviations from an individual's mean; Continuous Addition (half-hour); Cancellation of numbers (15 minutes duration); Triplet Numbers (10 minute auditory presentation of sets of numbers requiring various responses) ; Simplex GNV Intelligence Tests (chortened to 45 minutes duration).

Subjective thermal assessments by each subject were gained on each occasion using a seven-point scale, and related to 4 indices of warmth. Recordings of air and radiant temperatures, rates of air motion and humidity were made in two central positions in the rooms at several times during each testing period. During practice sessions with each class, the general purpose of the study was explained, but not the methods of scoring. Apart from a verbal emphasis for speed and accuracy, no other motivation was attempted, and the repeated sessions (varying in number for different groups) were incorporated into the regular time table at specific times and days of the week. Only the investigator was present at any time, and all procedures were standardized.

Individual scores were treated separately, but the samples included the results from different classes. Since scoring was either in the form of the Ratio Score (previously found to be independent of age and ability) or deviations from an individual's own score, the differences between pupils from the different schools were not expected to be significant.

Optimum thermal comfort levels were established by regression analysis and a comfort zone was delineated to include 60% of the total sample - the largest percentage which could be actually included in any range (see Table 5).

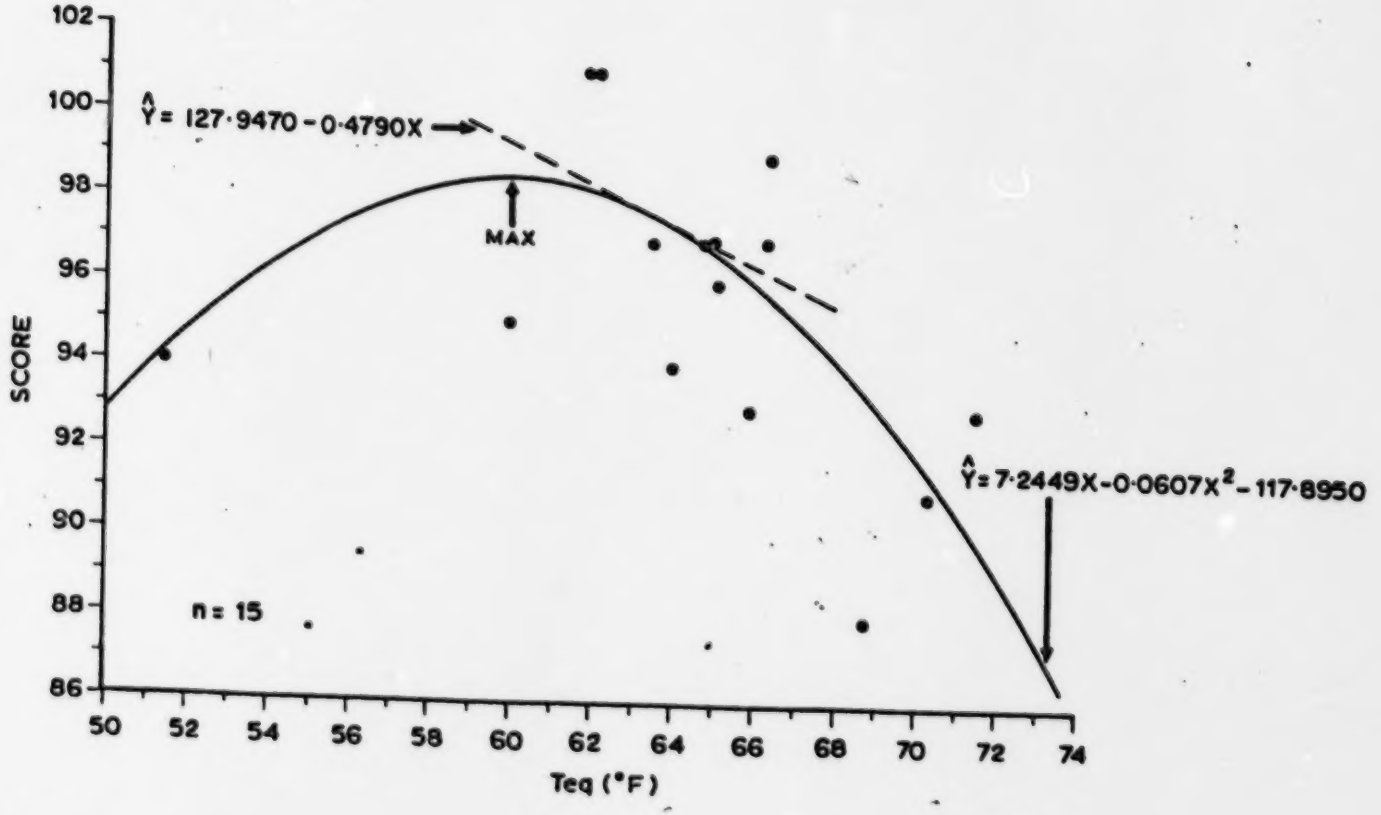
BOYS' PAULI ONE HOUR MEAN RATIO SCORES AGAINST Teq



(FIG. 3)

28a

GIRLS' PAULI ONE HOUR MEAN RATIO SCORES AGAINST Teq



(FIG. 4)

226

TABLE 5. COMFORT AND PERFORMANCE AT CONTINUOUS ADDITION (ONE-HOUR) RATIO SCORE

	maximum comfort $^{o}F\ T_{eq}$	lower comfort limits $^{o}F\ T_{eq}$	upper comfort limits $^{o}F\ T_{eq}$	significance of quadratic regression P levels	position of maximum performance $^{o}F\ T_{eq}$	significance of linear regression P levels	number of sessions	number of individuals
combined	61.7	58.5	68.4	<0.001	59.4		24	444
girls	61.9	58.5	68.4	<0.05	58.7	<0.05	15	187
boys	60.8	58.5	68.4	<0.01	59.7	<0.05	24	257

Although there was a general lack of information at lower temperatures, computerized regression of scores on a quadratic function of warmth produced significant associations and maximum points with the Continuous Addition (one-hour) Ratio Scores. Treatment of boys and girls as separate sub-samples provided a check for internal consistency, in both cases showing almost identical positions of maximum performance, at temperatures below thermal neutrality (Table 5). Since these maxima were located at the lower end of the comfort zone, a check was made to see whether significant decreases of performance did occur before its upper limits. Performance data only within the zone were retained and regressed on the thermal indices separately for boys and girls. The reductions in performance were significant for the boys Ratio Score ($P < 0.05$) and almost so for the girls (Fig. 3 and 4). Similar procedures were employed for the total additions, and although no significant quadratic curves were obtained, reductions within the comfort zone were significant with boys ($P < 0.05$) and girls ($P < 0.01$). No other associations were found of interest to the

present discussion.

The author suggests that optimum environments for mental work involving a high degree of concentrated effort are located below subjective thermal neutrality, in conditions which may be described as "comfortably cool". This is based on the results of only one type of task, and a sample relating to a particular geographic area and age-activity group. Obviously this suggestion is only regarded as an hypothesis which must be verified by other research.

Although in many ways approximating a real life situation, there still existed an element of artificiality in the kind of tasks performed. Since associations were observable only with a task which must be regarded as extreme in the amount of effort involved, the results overall seem to indicate only slight thermal influences on more usual work in non-air conditioned schools. Moreover, Auliciems has heavily relied upon the validity of a factor analysis interpretation of the main test by Reuning (1957). It must be noted that this interpretation had been based on a young adult sample, and the precise meaning of the Ratio Score, and Total Additions which disregards errors, is open to speculation. It would appear, however, that a highly concentrated effort was needed for the attainment of high scores.

There exists the lack of information on performance in cool conditions, and it may be questioned whether the maxima might not have actually occurred at uncomfortably cool temperatures had a sufficient number of these been observed. The author admits this possibility and the recommended "comfortably cool" sensation is made from practical considerations which do not permit stress sensations as acceptable. Obviously

also, the "comfortably cool" sensation refers to a single subject, since such a mean would indicate cold stress for a large proportion of any group of people.

DISCUSSION AND CONCLUSIONS

Research within the last 25 years has demonstrated that human performance does vary within differing thermal levels. A universal optimum warmth, however, is not possible to define for a variety of reasons, which may be classed as individual (physiological or psychological), social or physical. As for any other dimension of human behaviour, definition of optima of any kind can only hope to delineate a norm and recognize a wide distribution of responses about this norm.

In the case of physiological, and their related psychological responses to the thermal stimulus variability has been associated with a multitude of factors ; age, sex, basal metabolic rate, state of acclimatization, time of day and year, time of food ingestion, and recently states of weather (Auliciems 1969b). Past evidence nevertheless, has shown that relatively homogenous populations varying mainly in individuality of bodily functions do tend to comply with a normal distribution of responses, such as thermal sensations.

Thus also in experiments on human performance, mean group levels indicate the existence of maximum proficiency of achievement within some range on the thermal continuum. Even for strictly controlled samples however, no specific optimum thermal environments have been satisfactorily demonstrated, but rather ranges within which performance begins to deteriorate, as judged by statistical analysis.

In general, the impression until relatively recently has been that man's working ability is not influenced by atmospheric environments within the range of temperatures normally encountered, and the role of temperature has been largely dismissed by many authors. Mackworth (1950, p.149) himself stated that "... a rise of 5°F has no effect at all on human ability at ordinary atmospheric temperatures". Assuming this to be true, then in work situations a departure of 3°C (5°F) from neutrality would be inconsequential, yet this range would actually encompass the comfort zone as delineated by many authors. Viteles and Smith (1946, p.176) referring to mental performance confluded that for fully clothed subjects " ... for work periods not exceeding 4 hours... no adverse effects on performance are produced by an increase from 73 to 80°F (23.0 to 26.5°C) ET". It has been even suggested that performance may actually improve in moderate levels of thermal stress (Bartlett and Gronow 1953; Hutchinson 1941; Ketusinh et al 1967; Pepler 1969). Perhaps then it is not surprising that a survey of standard textbooks of psychology reveals that in the majority of cases no mention is made of thermal environments. The rare exceptions which deal with thermal effects do so very summarily. For example, Boring, Langfeld and Weld (1956) and Maier (1955) refer only to the very early studies of the 1920s and Maier (1955, p.554) states that "... mental work may be performed as effectively under humid ....., hot and stagnant air conditions as under optimum conditions ...".

Considering the findings of Mackworth, Morgan (1956) and Anastasi (1964) primarily refer to the high temperatures at which a loss of performance appears to occur. However,by not stressing the semi-nude state of the subjects, these authors

fail to point out their relatively elevated neutrality. With thermal neutrality as a point of reference, the interpretation of Chapanis, Garner and Morgan (1949) is evidently fallaceous. The latter wrote "... although the most comfortable working environment may be at a temperature of about 65 degrees, performance does not begin to deteriorate until temperatures of about 87½ and 92 degrees are reached" (Chapanis, Garner and Morgan, 1949, p. 399). Apart from the mistake introduced by Mackworth in using the incorrect normal scale of ET, the optimum comfort of the subjects would not have been 65°F (18.5°C) ET, but much higher due to the state of dress and some degree of acclimatization. Webb's (1959) investigation of the comfort of Singapore residents, wearing light clothing or stripped to the waist, showed optimum at approximately 26°C (78°F) ET (77°F ET if the basic scale, or 79°F ET if the normal scale is used). It must also be remembered that the neutral zone of man in the basal state is at approximately 28-31°C or 82-88°F (Gagge et al 1938; Hardy and Soderstrom 1938), which converted to ET using the appropriate basic scale would approach 24-27°C (76-81°F) ET with moderate humidity of 50-60% and still air conditions.

While no convincing case has been presented in the laboratory experiments to locate optimum conditions for mental performance, nor to show decrement within relatively normal thermal environments, certain indications exist to suggest that the sensitivity of performance to temperature may be often underestimated. Of importance is Pepler's (1958) finding of performance decrement only 3°C (5°F) ET above and below what he believed was optimum. Although his subjects, being semi-nude and acclimatized to the equable temperatures of the tropics, could have been expected to have a narrower

zone of vasomotor regulation than that of fully clothed people in more temperate climatic areas, his results have shown an optimum performance range of temperatures relatively close to that normally experienced.

If a greater sensitivity to thermal levels does exist, the question arises, why has there been so little experimental evidence in support? Several factors may be held to account, not the least being the purely arbitrary temperature control in the majority of cases. For example, Mackworth (1950) used thermal levels varying in steps of 3°C (5°F) in dry and wet-bulb temperatures. The microclimates of Pepler (1956) and Watkins (1956) varied in steps of 3-6°C (5-10°F) ET and those of Viteles and Smith (1946) 4°C (7°F) ET. In the case of Teichner and Wehrkamp (1954) and Russell (1957) the steps were wider still at 8°C (15°F) and 10°C (18°F) air temperature.

The use of such broad steps assumes the inconsequence of smaller variations in temperature and the thermal scale can be no more sensitive than its gradations. If decrement is observed on either side of any temperature, it does not necessarily follow that the particular temperature is optimum. More specifically, in Pepler's (1958) case, the discovery of loss of performance at 24 and 30°C (76 and 86°F) ET in comparison to 27°C (81°F) ET, does no more than indicate that conditions between 24 and 30°C (76 and 86°F) ET are preferable to those beyond. The conclusion of Teichner and Wehrkamp (1954), that man appears to be more sensitive to cold, was arrived at when decrement at 13°C (55°F) was found to exceed that at 29°C (85°F) in comparison to 21°C (70°F) air temperature. This conclusion would only be valid if 21°C (70°F) had been shown as optimum, but since no evidence was presented this

must be considered only an assumption. If the optimum had existed above 21°C (70°F), then the loss of performance may have possibly appeared symmetrical above and below this temperature.

Another readily observable failing, not always pointed out in subsequent references, is that of the lack of applicability of the results from laboratory experiments which almost invariably refer to a highly biased sample : fit young men, often trained for hardship by military service (Bursill 1958; Carpenter 1950 ; Mackworth 1946, 1950 ; Pepler 1956, 1958; Teichner and Wehrkamp 1954; Viteles and Smith 1946 ; Watkins 1956). In view of this factor, the evidence of man's resiliency to thermal hardships is not surprising, but it may be questioned whether this insensitivity is representative of the population at large.

Moreover, most experiments have been designed to standardize the degree of effort by the subjects through the use of bonus payments. Although Mackworth believed that incentives did not influence the level of performance, the contrary was demonstrated by Pepler (1956) and Watkins (1956) who showed that scores tended to deteriorate more rapidly without rewards.

It can be reasonably argued that the relatively immediate rewards, and also the artificiality of laboratory situations, have tended to negate the voluntary aspects of performance and to produce efforts which can be hardly considered as typical of normal work (Wyndham 1964). It has been implied by several authors (Bedford 1948 ; Cattell 1941 ; Givoni and Rim 1962 ; Lee 1940 ; McFarland 1953 ; Pepler 1964) that while moderate stress conditions may not actually affect ability for performance, willingness to work may be reduced. Since in everyday situations most activities are voluntary to a very large

degree, for practical considerations the important question does not seem to be "What is man capable of doing", but rather "What is he likely to do?" The experimental evidence, in the main, has been concerned with the former question and therefore the validity of the conclusions may be questioned when applied to normal work situations. Certainly everyday subjectives (and largely volitional) experiences would seem to indicate that even relatively small departures of temperature from an optimum have some effect on working efficiency. For example, Stamp (1964, p.44) states "All I know, personally, is that I am quite incapable of work, mental or otherwise, if I am sensibly cold".

It would appear that particularly the studies in school situations confirm the latter contention, since in all cases performance has incorporated a large measure of volition not normally present in laboratory experiments. The preceding evaluations of each investigation has illustrated various shortcomings either in methodology or interpretation. In isolation, of course, no single study provides irrefutable proof of thermal effect, but an overall view does show quite conclusively that mental performance is associated to physically recorded parameters of warmth typical of school environments. Without further assessment of the relative merits or validity of each separate finding, comparison between the results is attempted in Table 6, which has been designed to display not so much the physical temperatures of performance maxima, but rather the subjective thermal experiences at these. In the table estimates of the positions of thermal neutrality are either based on those actually recorded (in schools by Pepler and Warner, 1968, and by Auliciems, 1972b), or estimated as ranges on the basis of likely metabolic

rates involved and the amounts of clothing as reported. Comparison was made between such estimated neutral temperatures and those at which performance decrements have been variously observed, but translated into probable sensations on a 9-point scale (from Table 7) in columns 5, 6 and 7 in Table 6. Although in all cases except Auliciems (1972b) these involve considerable guesswork, a comparison is now possible between diverse populations and experimental situations.

In all results, maximum performance occurs close to neutrality (except those of the N.Y. State Commission on Ventilation, 1923, and Viteles and Smith 1946, both of which had obviously neglected testing in near-comfort environments). Subjectively the maxima fall within the range comfortably cool (-1) to comfortably warm (+1). The only study which attempted to provide a continuum of warmth (Auliciems 1972b) identified the optimum at comfortably cool, but as yet there is no other evidence to support this finding. Seemingly increased sensitivity to cold (Pepler 1958, 1971) had been observed with semi-nude men and children habitually exposed to equable warmth of the Tropics and air-conditioning respectively. In such circumstances, people are poorly equipped to cope with unexpectedly decreasing temperatures, and it is probable that the cold discomfort threshold had been only fractionally removed from neutrality. Since precise comfort data are not available for reliable estimation of the relative positions of sensations and performance maxima, it is impossible to conclude whether these results do actually contradict the identification of comfortably cool as optimum by Auliciems (1972b).

In conclusion, there is every indication that statistically detectable performance optima do exist even for groups of people, despite factors of individual variability. It

TABLE 6. PERFORMANCE AS A FUNCTION OF THERMAL SENSATIONS

(Unless indicated otherwise thermal levels refer to °F air temperature. Subjective sensations given on 9-spoint scale shown in Table 7)

	observed or estimated neutrality	observed maximum performance	observed work decrement		estimated thermal sensation		
			below neutrality	above neutrality	decrement below neutrality	maximum performance	decrement above neutrality
	1	2	3	4	5	6	7
Laboratory Experiment							
N.Y. State Commission on Ventilation (1923)	40-60	68	-	75	-	0 to + 2	+ 3
Vernon, Bedford & Warner (1930)	58-62	62	50	-	- 3	0 to + 1	-
Weiner & Hutchinson (1945)	60-70 ET	65-68 ET	-	91 ET	-	-1 to + 1	+ 3
Viteles and Smith (1946)	70-75 ET	73-80 ET	-	87 ET	-	-1 to + 3	+ 3
Mackworth (1945,1950)	77-79 ET	81 ET	-	86 ET	-	+ 1	+ 3
Carpentor (1950)	77-79 ET	81 ET	-	86 ET	-	+ 1	+ 3
Pepler (1956)	77-79 ET	81 ET	-	86 ET	-	+ 1	+ 3
Watkins (1956)	77-79 ET	81 ET	-	86 ET	-	+ 1	+ 3
Pepler (1958)	77-79 ET	81 ET	76 ET	86 ET	- 1 to - 2	+ 1	+ 3
Teichner and Wehrkamp (1954)	65-75	70	55	85	- 3	-1 to + 1	+ 3
Russell (1957)	65-75	68	50	86	- 3	-1 to + 1	+ 3
School Studies							
Seymour (1936)	58 (?)	58	54	-	-2	0	-
Peccolo (1962)	70-75	72-74	-	72-81	-	0 to + 1	0 to + 3
McCardle (1966)	70-75	70-74	-	70-79	-	0 to + 1	0 to + 3
Pepler & Warner (1968)	77	80	62	86	- 2	+ 1	+ 2
Pepler (1971)	75 (?)				- 1	0	+ 1
Auliciems (1972)	62-63	61	-	61-70	-	- 1	0 to + 2

TABLE 7. SCALE OF THERMAL SENSATIONS

Sensation	Numerical Value		
(excessively hot)	> + 3		
much too warm	+ 3		
too warm	+ 2		
comfortably warm	+ 1		comfort zone
comfortable	0	— neutrality	comfort zone
comfortably cool	- 1		comfort zone
too cool	- 2		
much too cool	- 3		
(excessively cold)	< - 3		

would also appear that in the comparative terms of thermal sensations there is a tendency for this to occur in the very narrow range of thermally comfortable temperatures subjectively perceived as pleasantly warm or cool. The indications are that if the individual factors were eliminated (e.g. by treatment of the results of individuals separately), a very precise subjective optimum could be estabished within the range. Obviously not all people are equally resistant to the effects of thermal strain, but there is no data at present available to show the degree of variability between individuals, although a very wide spread of thermal sensations has been observed in almost all comfort studies.

Pepler (1963) has listed a number of problem areas that need exploration, including the comparison of differential effects of heat on various types of tasks reflecting different physiological and intellectual functions. There appears to be very little evidence to date to suggest such differentials under normally encountered environments, particularly in the voluntary indoor type of working situations which involve a considerable mental component. Certainly such aspects of school (and any other) work as "rates of learning" and "levels of performance" are quite inseparable and more a matter of semantics of psychology.

The weight of evidence, especially in view of the results of the school studies, indicates that performance in the broadest sense is affected by thermal conditions of every day situations.

More studies are needed, however, to determine more precise and reliable optima, which should be expressed on a relative thermal scale of a psychological nature

to enable comparison between diverse populations. The following features of experimental design appear to be particularly desirable :

1. Thermal environments employed should closely approximate those normally encountered by the subjects.

2. Sampling should be made on a thermal continuum with emphasis placed on the subjective comfort range.

3. Performance levels, thermal responses and needs of each subject should be recorded separately, and statistical analysis should be planned to enable the inspection of each individual's results.

4. Measures of work performance and general working conditions should be as real life as possible and incentives such as bonus payments should not be offered.

REFERENCES

ANASTASI, A. 1964 : Fields of Applied Psychology. McGraw-Hill, New York.

AULICIEMS, A. 1969a: Thermal requirements of secondary schoolchildren in winter. J. Hyg., Camb. 67 : 59

AULICIEMS, A. 1969b : Effects of weather on indoor thermal comfort. Int. J. Biomet. 13: 147

AULICIEMS, A. 1972a : Some observed relationships between the atmospheric environment and mental work. Environmental Research 5 : 217

AULICIEMS, A. 1972b : The Atmospheric Environment. A study of comfort and performance. University of Toronto Department of Geography Research Publications, University of Toronto Press, Toronto.

BARTLETT, D.J. & GRONOW, D.G.C. 1953 : The effect of heat stress on mental performance. Flying Personnel Research Committee, FPR 846, Farnborough.

BEDFORD, T. 1948 : Basic Principles of Ventilation and Heating. Lewis, London.

BEDFORD, T. & WARNER, C.G., 1939 : Subjective impressions of freshness in relation to environmental conditions. J. Hyg., Camb. 39 : 498

BORING, E.G., LANGFELD, H.S. & WELD, H.P., 1956 : Foundations of Psychology. Wiley, New York.

CATTELL, R.B. 1941 : General Psychology. Sci-Art, Framingham, Mass.

CHAPANIS, A., GARNER, W.R. & MORGAN, C.T., 1949 : Applied Experimental Psychology. Wiley, New York.

FARMER, E., BROOKE, R.S. & CHAMBERS, E.G., 1923 : A comparison of different shift systems in the glass trade. Rep. ind. Fatigue Res. Bd. No. 24, London.

GAGGE, A.P., WINSLOW, C.E.A. & HERRINGTON, L.P., 1938 : The influence of clothing on the human body at varying environmental temperatures. Am. J. Physiol. 124:30.

GIVONI, B. & RIM, Y., 1962 : Effects of the thermal environment and psychological factors upon subjects' responses and performance of mental work. Ergonomics, 5 : 99.

HARDY, J.D. & SODERSTROM, G.F. 1938 : Heat loss from the nude body and peripheral blood flow at temperatures from 22°C to 35°C. J. Nutr. 21:383

HANSEN, B.P., 1966 : A study of the Effects of Room Temperature on Learning, PhD. dissertation, University of Iowa.

HUTCHINSON, F.W., 1941 : Health vs. comfort vs. efficiency. Heat. Vent. Engr. J. Air Condit. 38 : 28

KETUNSINH, O., DONAVANIK, T., & CHETANAJEDIN, P., 1967 : Assessment of moderate thermal stress in naturally acclimatized individuals. In Biometeorology, vol. 2, Proceedings of the 3rd International Congress, ed. S.W. Tromp and W.H. Weihe. Pergamon, Oxford.

LEE, D.K., 1940 : Reported by Critchley, M. 1947 : Effects of climatic extremes. Br. J. ind. Med., 4 : 164.

LINK, J.M. & PEPLER, R.D., 1969 : Associated fluctuations in daily temperature, productivity and absenteeism. Draft of a paper submitted for presentation to the ASHRAE convention in Kansas City, June 1970.

MACKWORTH, N.H., 1946. Effects of heat on wireless operators hearing and recording morse code messages. Br. J. ind. Med. 3 : 143

MACKWORTH, N.H., 1950 : Researches on the measurement of human performance. Med. Res. Coun. Spec. Rept, No. 268, London.

McCARDLE, R.W., 1966 : Thermal Environment and Learning. Ph.D. dissertation, University of Iowa.

McFARLAND, R.A., 1953 : Human Factors in Air Transportation, McGraw-Hill, New York.

McNALL, P.E. & NEVINS, R.G., 1967 : Comfort and academic achievement in an air-conditioned Junior High School - A summary evaluation of the Pinellas Country experiment presented to ASHRAE Annual Meeting, Minneapolis, Minn., June 26-28, 1967.

MAIER, N.R.F., 1955 : Psychology in Industry, 2nd ed. Houghton Mifflin, Boston.

MORGAN, C.T., 1956 : Introduction to psychology. McGraw-Hill, New York.

NEW YORK STATE COMMISSION ON VENTILATION, 1923: Report on Ventilation Dutton, New York.

OSBORNE, E.E., VERNON, H.M. & MUSCIO, B. 1922 : Two contributions to the study of accident causation. Rep. ind. Fatigue Res. Bd. No. 19, London.

PARTRIDGE, R.C. & MACLEAN, D.L., 1935 : Determination of the comfort zone for school children. J. industr. Hyg., 17 : 66.

PECCOLO, C.M., 1962 : The Effect of Thermal Environment on Learning, Ph.D. dissertation, University of Iowa.

PEPLER, R.D., 1956 : Environmental warmth and performance, Ph.D. dissertation, Cambridge University.

PEPLER, R.D., 1958 : Warmth and performance : an investigation in the tropics. Ergonomics, 2 : 63.

PEPLER, R.D., 1963 : Performance and well-being in heat. In Temperature, its measurement and control in science and industry. Vol. 3, ed. C.M. Hazfeld, Reinhold, New York.

PEPLER, R.D., 1964 : Psychological effects of heat. In Heat Stress and Heat Disorders. by C.S. Leithead and A.R. Lind, Cassell, London.

PEPLER, R.D., 1971 : Variations in students' test performances and in classroom temperatures in climate controlled and non-climate controlled schools. Presented to ASHRAE Annual Meeting, Washington, D.C., August, 22-25, 1971.

PEPLER, R.D. & WARNER, R.E., 1968 : Temperature and learning : an experimental study. Presented at ASHRAE Annual Meeting, Lake Placid, New York, June 24-26, 1968.

REUNING, H., 1957 : The Paul Test - new findings from factor analyses. J. Nat. Inst. Personnel Res. 7 : 3.

RUSSELL, R.W., 1957 : Effects of variations in ambient temperature on certain measures of tracking skill and sensory sensitivity. U.S. Army Med. Res. Lab. Rep., No. 300, Fort Knox.

SEYMOUR, A.H., 1936 : The Effects of Different Conditions of Temperature and Ventilation on the Mental Output and Mental Fatigue of School Children. Ph.D. dissertation, University of London.

STAMP, L.D., 1964 : Some Aspects of Medical Geography. Oxford University Press, London.

TEICHNER, W.H. and WEHRKAMP, P.F., 1954 : Visual motor performance as a function of short-duration ambient temperature. J. exp. Psychol. 47 : 447.

VERNON, H.M., 1918 : An investigation of the factors concerned in the causation of industrial accidents. Health of Munitions Workers Committee Memo, No. 21, London.

VERNON, H.M., 1919 : The influence of hours of work and ventilation output of tinplate manufacture. Rep. ind. Fatigue Res. Bd. No. 1, London.

VERNON, H.M., 1920 : Fatigue and efficiency in the iron and steel industry. Rep. ind. Fatigue Res. Bd. No. 5. London.

VERNON, H.M., BEDFORD, T. & WARNER, C.G., 1927 : The relation of atmospheric conditions to the working capacity and the accident rate of miners. Rep. ind. Fatigue Res. Bd. No. 39, London.

VERNON, H.M., BEDFORD, T. & WARNER, C.G., 1928 : A study of absenteeism in a group of ten collieries. Rep. ind. Fatigue Res. Bd, No. 62, London.

VERNON, H.M., BEDFORD, T. & WARNER, C.G., 1930 : A study of heating and ventilation in schools. Rep. ind. Hlth Res. Bd. No. 58, London.

VERNON, H.M., BEDFORD, T. & WARNER, C.G., 1931 : Two studies of absenteeism in coal mines. Rep. ind. Hlth Res. Bd. No. 62, London.

VITELES, M.S. & SMITH, K.R., 1946 : An experimental investigation of the effects of change in atmospheric conditions and noise upon performance. Trans. Am. Soc. Heat. Vent. Engrs. 52 : 167.

WATKINS, E.S., 1956 : The Effects of-Heat on Psychomotor Efficiency with Particular Reference to Tropical Man, M.D. thesis, Liverpool University.

WEBB, C.G., 1959 : An analysis of some observations of thermal comfort in an equatorial climate. Br. J. ind. Med. 16 : 297

WEINER, J.S. & HUTCHINSON, J.C.D., 1945 : Hot humid environment : its effect on the performance of a motor co-ordination test. Br. J. ind. Med, 2 : 154

WESTON, H.C., 1922 : A study of efficiency in fine linen weaving. Rep. ind. Fatigue Res. Bd. No. 20. London.

WYATT, S., FRASER, J.A. & STOCK, E.G.L., 1926 : Fan ventilation in a humid weaving shed. Rep. ind. Fatigue Res. Bd. No. 37, London.